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CORRELATION BETWEEN TEXTURE OF HYDROXYAPATITE AND MECHANICAL ANISOTROPY IN LOXODONTA AFRICANA IVORY

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Samples of Loxodonta africana ivory were subjected to X-ray diffraction studies which showed that the hexagonal crystals have a strong preferred orientation with their basal planes perpendicular to the longitudinal axis of the tusk. Cylindrical samples were also machined from the tusk with cylinder axes along and perpendicular to the longitudinal axis of the tusk respectively. Three-point bending tests were performed on the cylindrical samples. The results show a clear anisotropy in the bending strength along the two directions. The sample with cylindrical axis longitudinally aligned shows less bending for the same applied force. The results verify a correlation between orientation of hydroxyapatite and, among other things, the mechanical strength. This may be related to the function of the tusk which with normal usage has to be able to sustain large bending forces in a direction normal to the longitudinal axis.

KEY WORDS: Ivory, preferred orientation, anisotropy, X-ray diffraction, tensile strength, hydroxyapatite

INTRODUCTION

It has been shown by ourselves [1] and others [2, 3] that the hydroxyapatite mineral phase in ivory has a preferred orientation. It is to be expected that this preferred orientation of the dental micro-structures may result in macroscopic mechanical anisotropy of the tusk. An anisotropy in microhardness has indeed been reported by Cui *et al.* [2] It is further reasonable to look for a relation between existing anisotropy and macroscopic function of the tusk. In this paper we report on the results of three-point bending measurements on cylindrically machined ivory samples of different orientation and compare our results with our X-ray diffraction data for modern African elephant ivory.

GEOMETRY AND EXPERIMENTAL PROCEDURE

Mechanical Testing

Figure 1 defines the co-ordinate system which was used. A typical Elephant tusk is cone shaped (almost cylindrical over most of its length) and has a smooth upward curve. The existence of the longitudinal radius of curvature, R_l, suggests that there may be a gradient in density of dental material along the v-axis as indicated in Figure 1 (b).

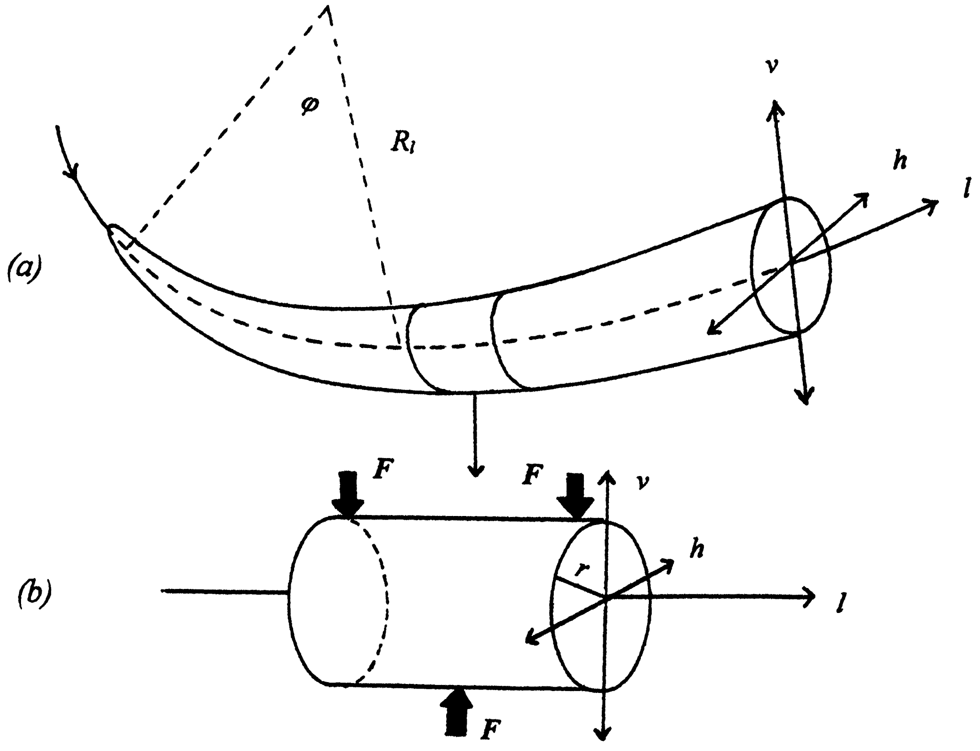

Figure 1 (a) Schematic of an elephant tusk showing the co-ordinate system adopted. Here *l* indicates the longitudinal direction, *v* the vertical direction, and *h* the horizontal direction. (b) Cylindrical approximation of a longitudinal section indicating typical bending forces expected during normal use of the tusk.

Under normal "working" conditions the tusks are expected to be mostly subjected to bending forces of the nature indicated in Figure 1(b), i.e. the forces will be approximately perpendicular to the *l*-axis and will result in a tendency to change the local R_l. The forces, however, need not be in the *vl*-plane as indicated in Figure 1(b). In order to relate the crystal orientation and normal tusk function with measured mechanical strength we performed three point bending tests on three different sample types. All three samples were machined from a single tusk. They were cylindrical with a diameter of 5 mm and a length of 70 mm and were selected from the same longitudinal section (approximately in the middle of the tusk). Samples A and B were machined with cylinder axis in the direction of the longitudinal axis of the tusk. They differ in the fact that sample B comes from a region close to the upper surface of the tusk (positive *v*-value) while A comes from a region close to the bottom of the tusk (negative *v*-value). Sample C was machined with cylinder axis along the *h*-axis of the tusk.

Three-point bending tests were performed on the three samples which were supported at the end points while the applied force (measured by means of a calibrated load cell) was applied in a direction normal to the cylinder axis and midway between the support points. The displacement of the centre point from the original cylinder axis was measured with a calibrated micrometer.

X-ray Diffraction

X ray diffraction patterns of two ivory samples, prepared from the same tusk were recorded. Sample XA was prepared with a polished flat surface in the *hv*-plane while sample XB was prepared with a polished flat surface in the *vl*-plane (See Figures 1(a) and (b) for directional information).

The diffraction patterns were recorded on a Siemens D500 $\theta/2\theta$ X-ray diffractometer. A Copper tube ($k_{\alpha 1}$ = 1.5406 Å) was operated at 30 mA, 40 kV (no $k_{\alpha 2}$ stripping was done). Divergence and receiving apertures of 1° and 0.05° respectively were selected and diffraction patterns were accumulated at 1s integration per point in steps of 0.02°.

EXPERIMENTAL RESULTS

The results of the three point bending tests are shown in Figure 2. For one and the same applied force, less bending was observed for samples A and B than for sample C. There was also a statistically significant difference between the responses of samples A and B respectively, apparently due to the different regions of origin as described in Section 2.

Figure 3 shows the X-ray diffraction patterns for powdered elephant tusk and the two samples XA and XB with the (002) peak and the shoulder of the (300) peak indicated. The main structure to the left of the (300) shoulder is a convolution of the (300), (211) and (112) reflections. Let the ratio I_{002}/I_{300} be indicated by R_t, R_{hv} and R_{vl} for the powdered tusk sample XA and sample XB respectively. Figure 3 then shows

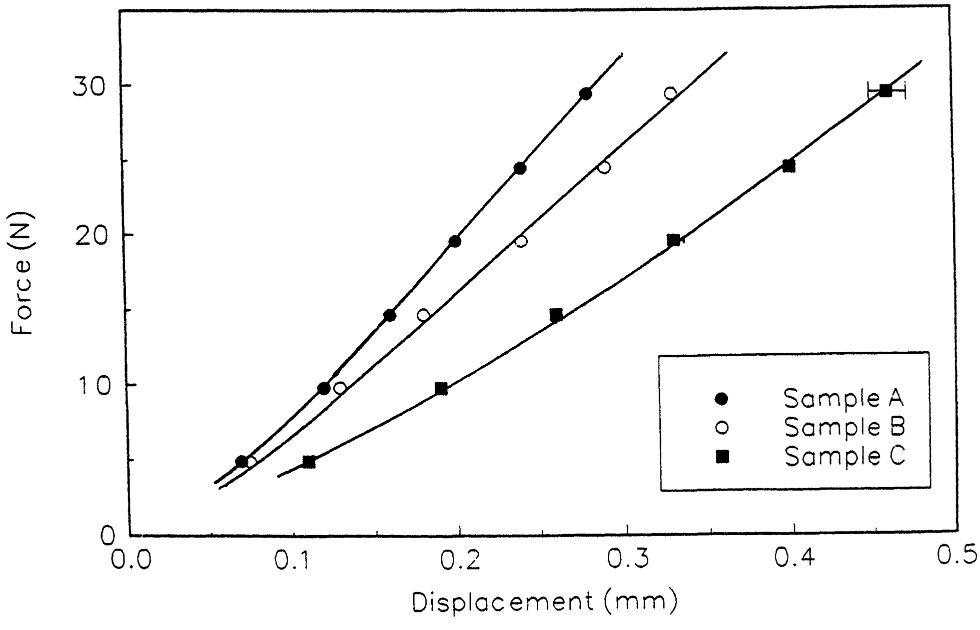

Figure 2 Graph of three-point bending force versus central displacement.

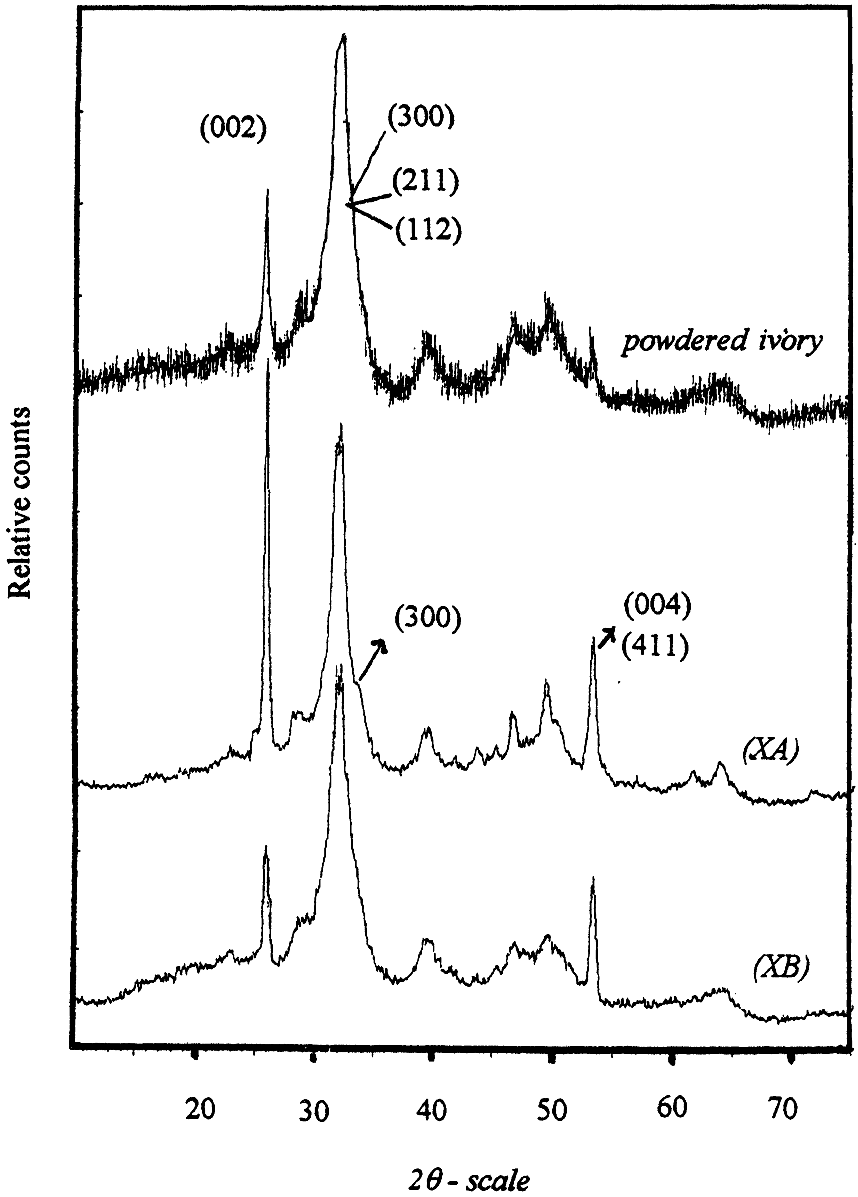

Figure 3 X-ray diffraction patterns (top to bottom) of powdered ivory, the *hv*-plane and the *vl*-plane respectively.

(using any convenient consistent baseline definition) that $R_{vl} = R_t \approx 0.4$ and $R_{hv} \approx 1.2$, thus indicating a clear directional anisotropy of hydroxyapatite orientation. The result shows that the hexagonal hydroxyapatite crystals have their basal planes by preference in the *hv*-plane.

CONCLUSIONS AND DISCUSSION

Both mechanical properties and hydroxyapatite texture show distinctive anisotropic properties in the tusk of Loxodonta africana.

Hydroxyapatite (Calcium Hydroxide Orthophosphate) is the major constituent of natural ivory although the latter is a highly structured compound material with a network of supporting collagen fibres [4]. Hydroxyapatite belongs to the Hexagonal crystal system of the $P6_3/m$ space group. The lattice parameters are a_0 = 9.418 Å and c_0 = 6.884 Å indicating a hexagonal unit cell of low aspect ratio c_0/a_0. It thus seems intuitively correct that preferred orientation with basal planes in the *hv*-plane will result in a composite structure which is more resilient to the bending forces likely to occur during every day use of the tusks (See Figure 4).

The difference in rigidity between A and B may be an indication that the natural curvature of the tusk is the result of anisotropy in the micro-structure.

The results suggest that the preferred orientation of hydroxyapatite in Loxodonta africana may be the result of an evolutionary advantage.

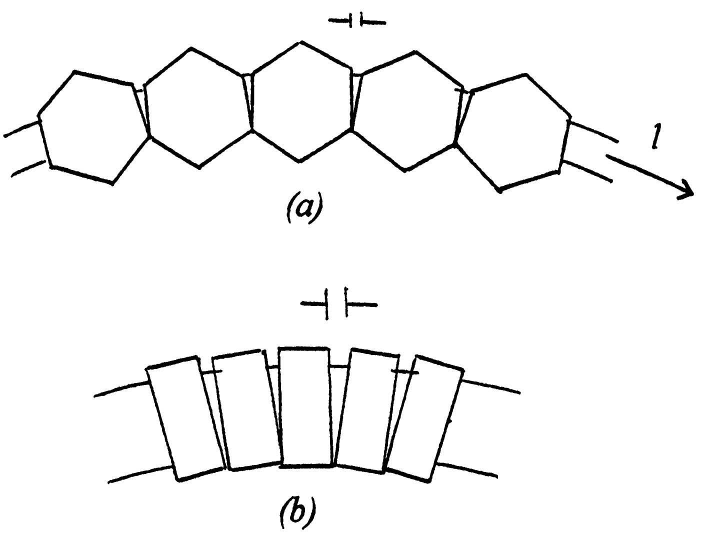

Figure 4 Schematic of two possible orientations of hydroxyapatite crystals along the longitudinal direction. As a result of the small c/a ratio it is conceivable that bigger forces may be needed to cause a given radius of curvature for orientation (b) than for (a).

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